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Development and Launch of the World's First Orbital Propellant Tanker

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ABSTRACT

This paper describes the development of Orbit Fab's Tanker-001 Tenzing mission, the world's first orbital propellant tanker. The development of a robust orbital propellant supply chain is critical to accelerating the growth of government and commercial space activities. The widespread availability of spacecraft refueling has the potential to provide a number of revolutionary benefits. High-value space assets could have their operational lives extended, as they would no longer be constrained by the amount of propellant stored onboard for maneuvering. On-orbit servicing missions would become more efficient, as servicing vehicles could be refueled and repeatedly used. A large orbital propellant supply would also enable new mission and business models based on operational flexibility and frequent maneuvering. These benefits would be particularly impactful on small satellites, where the ability to refuel could overcome the operational constraints of having smaller propellant tanks. This will greatly expand the market for small spacecraft as it increases their range of missions and capabilities.

Launching no earlier than June 24, 2021, Tenzing is a 35 kg small satellite with an Astro Digital bus carrying a supply of storable propellant, high test peroxide (HTP). Tenzing's propellant supply is being offered to customers for refueling and used to gather data on propellant storage. In addition to being the first propellant tanker, Tenzing is also an orbital laboratory including a variety of payloads intended to test key technologies for refueling. This includes the first flight of Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI), a stereo camera system, and a Halcyon HTP propulsion system designed and built by Benchmark Space Systems for orbital maneuvers. The latter two elements can be used to test rendezvous and flyby maneuvers, providing data to support the development of full rendezvous, proximity operations, and docking (RPOD) systems for future Orbit Fab missions.

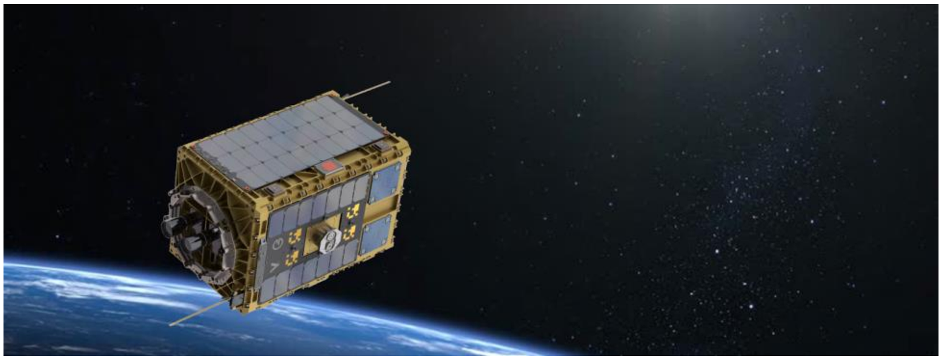

Figure 1: A render of Tanker-001 Tenzing in orbit

INTRODUCTION

Current spacecraft missions are constrained by finite supplies of fuel on board. They are limited to single use lifetimes and restricted from high mobility operations. The ability to refuel spacecraft at all scales on orbit and at various locations will fundamentally change astronautics and enable new use cases for small sats.

For an end-to-end refueling infrastructure to exist, three categories of challenges must be overcome. Those challenges are financial, technical and logistical in nature. Propellant solution providers must develop business models that create value; develop technologies for docking, propellant transfer and metering; and then finally build, launch and maintain a network of tankers in orbit.

Orbit Fab takes the first big leap with the Tanker-001 Tenzing mission (shown in Figures 1 and 2), which is the first of many propellant depots to be built by Orbit Fab and launched into Earth orbit. This mission builds upon the fluid transfer work Orbit Fab demonstrated on the ISS with Project Furphy[1]. On Tenzing, Orbit Fab leverages small sat economics to fly a functioning on orbit tanker while also flying risk reduction and technology development payloads for future missions. Tenzing payloads include subsystems and sensors for Rendezvous, Proximity Operations and Docking (RPOD). These include cameras and fiducials which will serve as the core of a fully cooperative and prepared RPOD system for in-space refueling.

Figure 2: CAD Render of the spacecraft exterior

Spacecraft Mission Objectives

Tanker-001 Tenzing has many exciting objectives that will help Orbit Fab and its partners take the next step towards their vision of a future space industry. It will make history as the first orbital propellant depot by storing and supplying high test hydrogen peroxide (HTP) to customers in space. It will also act as an in-space laboratory, allowing Orbit Fab and its partners to test future technologies that will be critical to orbital refueling operations and other satellite servicing activities. Its success significantly reduces the technical risk of future tankers, and supports Orbit Fab's long-term goal of operating a system for satellite refuelling in space.

Tenzing was named for Tenzing Norgay, the Sherpa who was first to the summit of Chomolungma (Mount Everest) in recognition of all the unsung heroes who support and enable exploration. The mission patch for the Tanker-001 Tenzing Mission is shown in Figure 3.

Figure 3: Tenzing Mission Patch

Spacecraft Layout and Capabilities

Tanker-001 Tenzing consists of a microsat bus derived from an Astrodigital Corvus 16U bus and payloads from multiple partners. The primary payload is Orbit Fab's refueling system which contains a propellant tank, filled with HTP, and two service valves compatible with Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI) System. This fill/drain valve system is made up of a service valve, a ground coupling half, and a space coupling half. Tenzing will be the first flight demonstration of the RAFTI service valve. A RAFTI ground coupling half will be used to do the spacecraft ground fueling. Tenzing has a secondary Orbit Fab payload consisting of a rendezvous, proximity operations, and docking (RPOD) system. This payload is a technology demonstrator and risk reduction package with docking fiducials, and LEDs. It will serve as a demonstration of Orbit Fab's capabilities for future rendezvous and docking missions.

Orbit Fab's RPOD payload is supported by a SCOUT Inc. SCOUT-Vision spacecraft situational awareness payload, a stereoscopic camera system offering real-time local situational awareness, including experimental optical navigation, just-in-time collision avoidance, and high-resolution imaging capabilities for nearby space objects, debris, and spacecraft.

Another prominent Tenzing payload is the Halcyon Thruster, designed by Benchmark Space Systems. Halcyon is a hydrogen peroxide propulsion system that will enable Orbit Fab to demonstrate the ability to do rendezvous and docking operations in space.

Two Accion Systems' TILE2 thrusters are also on the spacecraft. TILE2 is an electric propulsion thruster and it is using this mission to verify its functionality through long- and short-duration firings, and to demonstrate restartability.

PAYLOAD OVERVIEW

This section details some of the major payloads on the Tenzing mission. In addition to being a propellant tanker, Tenzing is an orbital laboratory testing key technologies for future in-space refueling operations. For purposes of this paper, the focus has been placed on payloads that support this objective. Other secondary payloads were discussed briefly in the previous section but are otherwise beyond the scope of this paper.

Primary Tank System

The primary payload is a fluid system with a flanged diaphragm tank. The diaphragm is compressed between the flanges of both tank halves and separates the pressurant (gas) and fuel (liquid) halves of the system. The purpose of the primary payload tank is to store HTP and be able to transfer that propellant to another spacecraft. Metal tubing plumbs the primary payload tank into two discrete and isolated subsystems, one each for the gas and liquid halves of the system. Each subsystem terminates downstream into Orbit Fab's RAFTI service valve, and contains instrumentation and additional valving to control fluid flow during servicing and venting operations. A CAD render of the full primary tank payload system is shown in Figure 4.

Tank Requirements

Orbit Fab's propellant storage tank is the main component of the primary payload. This tank was designed, manufactured, assembled, and completed qualification- and acceptance-test campaigns on a rapid timetable. Mission requirements drove decisions throughout the development of the primary payload tank.

A major requirement was the timeline in which the tank needed to be developed. The schedule included less than six months from the start of the design phase to the delivery date of the primary payload system. This timeline drove a rapid requirements definition and system development schedule for the tank system.

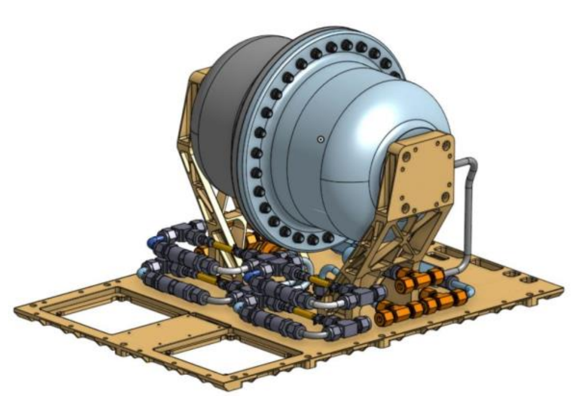

Figure 4: CAD render of the primary payload mounted to a structural panel

The structure of the primary tank needed to be sized such that it would survive the launch environment with a sufficient margin of safety while maximizing the internal propellant storage volume, and be light enough to meet the mass budget.

Another design factor was the volume the primary payload could take up within the spacecraft. Starting with the overall volume allowance, the tank was designed to be as large as possible, and then optimized for mass and manufacturability. The remainder of the primary payload, the fluid feed system, was then designed to fit around the primary tank in the spacecraft.

Material selection was another aspect in designing the primary tank, and many factors played a role in the decision. The biggest of these factors were demisability and material incompatibility. The tank was large enough that material requirements were imposed to ensure it wouldn't survive reentry. This along with HTP material compatibility led to the selection of aluminum as the primary tank material.

Every major decision pertaining to the primary tank was made after researching similar HTP fluid systems and analyzing all the requirements for this particular mission. These requirements helped shape the tank in many ways, but there were still many steps to be taken in the design of the diaphragm primary tank.

Tank Design Steps

For connecting the tank halves, bolted and welded flange designs were considered. While a welded flange is more volume efficient, HTP compatibility with welded materials is typically poor. The challenges of a welded connection could be solved, but at the expense of additional schedule risk. This led to the selection of a bolted flange. The flange was designed using classical methods and refined with finite element analysis (FEA), a sample of which is shown in Figure 5. The number of fasteners and fastener sizing was completed using standard equations[2].

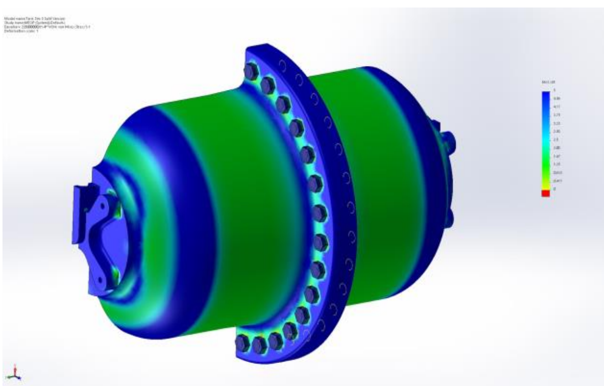

Figure 5: Results from a stress analysis of the primary payload tank

Flange gaskets and o-rings were considered for sealing the tank halves. Since this is a high pressure tank, o-ring glands were cut into the flange faces to reduce the risk of gasket blowout. A custom gland sizing tool was developed, allowing for rapid design iterations since all the design information was in one place.

Hemispherical, torispherical, and ellipsoidal end caps were considered. Hemispherical was eliminated due to low volumetric efficiency. The torispherical and ellipsoidal end caps are similar, but the ellipsoidal end caps have lower stress values and were selected. A relatively low ellipse ratio was selected to maximize the tank volume while still maintaining the necessary Margin of Safety.

Additional margin was added to the tank early in the design process. As unknowns were discovered later in the program, the additional margin carried from early in the program maintained safety margins while allowing rapid development.

Fluid Systems Overview

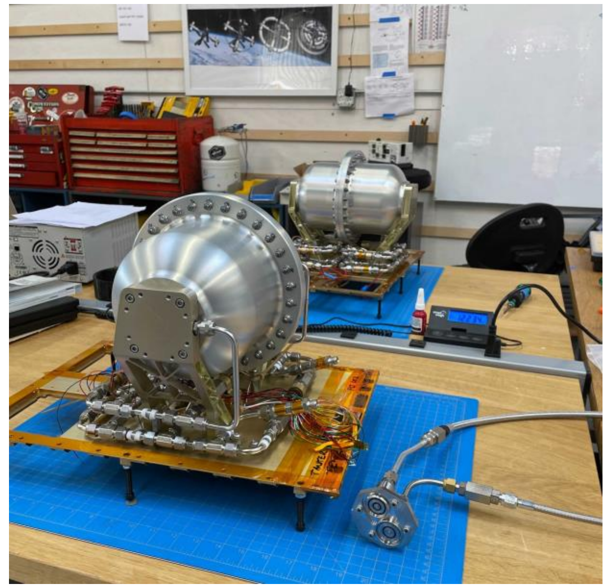

Figure 6: The flight and flight spare primary refueling systems built up at Orbit Fab's facility. A RAFTI Block 1 Ground Coupling half can be seen in the bottom right.

The fluid system architecture is the simplest configuration that meets the requirements for propellant leak inhibits. For ease of manufacture, the components were physically arranged symmetrically, within the available spacecraft volume. Multiple fitting types were considered for the system, including welded, flared, boss, and compression fittings. Compression fittings were ultimately selected due to their short lead times and relative ease of assembly. Welded connections were avoided due to the compressed mission schedule and the difficulty of performing rework on a welded system. Flared fittings, while easily reworked, presented challenges with tube fabrication in a restricted volume, whereas compression fittings allow bends slightly closer to the fitting. In future programs, where the schedule is less condensed and where higher system maturity reduces the need for potential rework, welds may be a better choice because of their superior leak performance and lower overall mass.

Down selection of the pressure transducers, solenoids, and check valves was primarily driven by material compatibility and lead time considerations. The main material concern was finding substances that did not cause rapid decomposition of high-test hydrogen peroxide. Because of the wide variety of materials that are incompatible with hydrogen peroxide, many COTS plumbing components were trivially ruled out during selection. However, the narrow range of permissible materials meant that finding components to meet all the necessary requirements was time consuming. Components with compatible materials often had very long lead times compared to their incompatible counterparts. In those cases, when possible, the short lead time item was procured and the incompatible materials were swapped out with compatible materials. For instance, COTS check valves were procured, and rebuilt to use HTP-compatible O-rings.

Historical data exists for hydrogen peroxide material compatibility, but this data is typically conservative since modern peroxide is less reactive then the peroxide available when the data was generated[3]. In addition to being conservative, much of the available data about hydrogen peroxide compatibility is incomplete, and multiple sources often report different results for the same generic material. There were only a few materials that received clearly positive results across the board. Because of this, efforts were made to choose plumbing components with wetted surfaces comprising only these known, compatible materials. The biggest challenges with material compatibility were with o-rings and other sealing materials inside valves. Each sealing material, even those from the same brand, has many different variants, and it was often difficult to get manufacturers to disclose the exact sealing material their product used. When there was no choice but to use materials with unknown compatibility, Orbit Fab generated a test plan to perform active oxygen loss (AOL) and stability testing with these materials. However, due to the heavy time restriction on the mission, some decisions on which materials to use had to be made before testing results were available. A couple of materials originally slated for use in the system were eliminated as a result of this testing and were replaced later in the program with materials that had higher compatibility.

The historical data and results from Orbit Fab's testing were used to generate a model of the oxygen generation rate over time. This was used to size the ullage space in the tank. Hydrogen peroxide decomposition is a function of surface area-to-volume ratio (S/V). For materials with a low S/V ratio, the historical data was used in modeling the oxygen generation rate since it had a low impact on the total oxygen generation rate. Since there are many assumptions in the model, a large amount of margin was added onto the analysis results.

Primary Payload Assembly

Once all the components of the primary payload had been manufactured, the tank halves and diaphragms were all inspected so that any problems identified could be quickly remedied at Orbit Fab's manufacturing facility. Dimensional and volumetric verification was performed on each tank and plumbing system to verify the tank met requirements. Every part of the assembly was cleaned and dried. All components in the wetted flowpath of the HTP fluid system were treated in order to minimize interaction between the HTP propellant and the base material. Treatments included but are not limited to passivation, anodization and conditioning with a lower concentration of HTP.

All of the fluid system components other than the primary tank were assembled in-place on one of the structural panels of the spacecraft. At this time, these components were tested to verify that no leaks were present, that all solenoids functioned as intended, and that all check valves opened at the correct pressures.

The primary payload tank was fully assembled and proof tested prior to being integrated into the remainder of the fluid system. For assembly, o-rings were lubricated and installed into their glands, and holes were punched into the diaphragm for fastener clearance. One half of the tank was placed atop the other half, and the flange fasteners were installed and torqued in a star pattern.

After assembly, the tanks were proof tested. During this proof test, tanks were filled to capacity with water and then pressurized. The tanks were visually inspected for leaks and maintained pressure, confirming they were properly assembled.

Once the tanks were proofed individually, they were integrated with the remaining fluid system on one of the spacecraft structural panels. The primary payload tank was integrated with the system via plumbing lines running to the tank ports. The tank brackets connected the tanks directly to the structural panel of the spacecraft. Once integrated, the complete fluid system was put through functional tests to confirm flow through the system.

Primary Payload Testing

After tank integration, functional testing, and checkouts were performed at Orbit Fab, the systems were sent to an external vendor for further testing. The tests completed in this testing campaign are outlined in Figure 6. Two of the tanks underwent a qualification test campaign, and two tanks were integrated into a system with plumbing for acceptance testing. Acceptance testing consisted of performing multi-axis vibration tests on a loaded tank, with leak checks between each cycle to verify that the tank could sustain flight loads. The qualification tests were similar to the acceptance tests, using higher loads and performing additional tests including pressure cycle and burst.

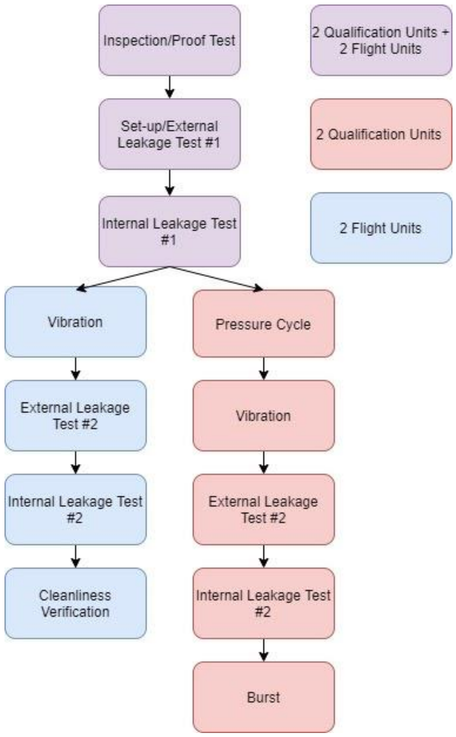

Figure 6: A flow diagram of the qualification and acceptance testing campaigns

All four units were subjected to an external helium leak test, where the tank system was enclosed in a bag and filled with helium, and the air in the bag was checked to measure the helium leak rate. After passing the external leak tests, each tank underwent a pressure decay test to ensure that there were no holes in the diaphragm inside the tank. This was done by loading nitrogen into one side of the tank until it could hold a constant pressure, indicating that the diaphragm had stopped moving and reached its fully extended position, and then monitoring the other side. At this point in the program, the testing plan for the qualification units and the acceptance units diverge. The qualification units moved on to pressure cycle testing, where they were filled with water (an acceptable test substitute for hydrogen peroxide) and then rapidly pressurized and depressurized with water for several dozen cycles. Although by analysis the tank can withstand several million cycles, this testing was performed to meet range requirements.

After the pressure cycle test, the qualification units moved onto vibration testing. The acceptance units moved straight from leak testing to vibration testing. All units were vibrated separately along each of their three axes, although the qualification units were vibrated for longer periods of time at higher loads. The tanks were all filled with water on one side of the diaphragm - the amount of water loaded was chosen to match the flight mass of the hydrogen peroxide. Nitrogen was loaded on the other side of the diaphragm and the system was pressurized (the acceptance units were pressurized to their maximum expected operating pressure and the qualification units were pressurized to a higher pressure).

After vibration testing, all four units went through another round of leak testing to ensure that the vibration did not do any damage. After verifying that they were not leaking, the acceptance tanks went on to be cleaned, while the qualification tanks went to burst testing. The tanks were pressurized to their design burst pressure, and then the pressure was ramped until failure. The tanks reached a pressure many times greater than its operating pressure. The testing campaign was successful for all units and confirmed the analysis that Orbit Fab had done. After testing, the qualification units were sent back to Orbit Fab's facility to be disassembled and inspected, the flight spare unit was put through more testing with hydrogen peroxide, and the flight unit went on to be integrated at the spacecraft level.

Primary Payload Software

The primary tank's instrumentation and actuation is controlled through an Astro Digital Thruster Control Unit (TCU2) programmed with micropython. This embedded system performs thermal control for the primary tank and secondary payloads and passes telemetry to the primary flight computer. Tank instrumentation data is sent back at set frequencies depending on the commanded state of the TCU2, with the ability to send telemetry at a frequency of up to 10 Hz. Collecting data on thermal control, system pressure changes, and actuator performance is critical to validating the performance of the first orbital propellant tanker. This data will support the design and development of future propellant tankers, reducing key risks for the implementation of future, larger tanks.

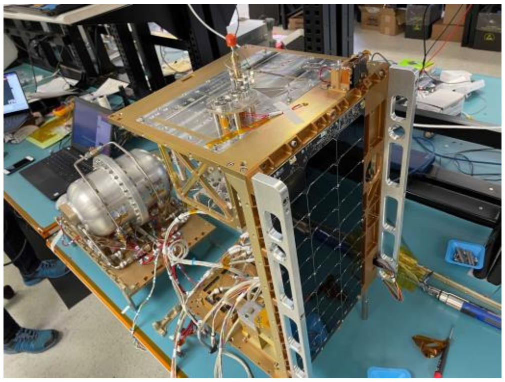

Figure 7: The Halcyon and Primary refueling tank during integration with Tenzing and software checkout.

An engineering model was established as a flight spare with plumbing and instrumentation that is functionally identical to Tanker-001 Tenzing. This engineering model is currently undergoing a self-pressurization test. The flight spare was filled with HTP and the system's self-pressurization rate is monitored over time. This integrated test validated the self-pressurization model. Data was collected from the four pressure transducers on the flight spare every minute. The test computer verifies spacecraft aliveness on a fiveminute alarm interrupt that is reset with each incoming telemetry packet. Test computer status is verified every three hours with messages sent directly to team members for real time verification. At the time of writing, the self-pressurization falls within predicted and acceptable mission parameters.

RPOD DEVELOPMENT PAYLOAD

In addition to the primary propellant tank system, Tanker-001 Tenzing carries several hardware and software payloads which will be used to test and validate key technologies to enable Rendezvous, Proximity Operations, and Docking (RPOD). RPOD is a critical technology for many future on-orbit activities necessary for building up the economy in space, including refueling and on-orbit servicing, assembly, and manufacturing (OSAM). While RPOD has been achieved successfully before, it has most commonly been implemented for large crewed systems and has always involved significant non-recurring engineering and R&D efforts. The objective of the RPOD test payloads on the Tenzing mission is to gain in-house operational experience with key technologies as well as generate data to support further development of RPOD systems with reduced cost and timeline burdens. This will help to boost commercial adoption of RPOD[4] and enable a rapid expansion of the economy in space including refueling and OSAM activities.

Passive RPOD Subsystem

RPOD systems are often divided into passive and active halves. The active half is the half which moves during proximity operations to achieve docking alignment while the passive half continues in its original orbit without maneuvering. One key barrier to making RPOD an easily achievable process for a variety of space missions is the creation of a low-SWaP-C passive half that enables cooperative and prepared RPOD, which is significantly easier to achieve than uncooperative and unprepared RPOD. To this end, Orbit Fab is working to develop a passive half that will provide necessary alignment features (i.e. fiducial markers) and status indicators (i.e. LEDs) in a package that integrates easily with docking adaptors such as the RAFTI service valve. Fiducial markers are symbols which have a defined unique appearance from different directions enabling them to serve as position indicators for optical imaging systems[5]. They were selected for use as their low mass and completely passive operation makes them ideally suited to spacecraft relative navigation. The use of LEDs allows the passive system to communicate basic status information without the mass and power penalties associated with high-powered processing and direct inter-spacecraft radio communications equipment.

A prototype of this system has been included on the Tenzing spacecraft (Figure 8). The passive RPOD system has been designed to integrate with an Astro Digital solar panel system and configured to wrap around the RAFTI service valve. This places the fiducials and indicators in an ideal location to facilitate docking using RAFTI while minimizing impact on system budgets. Four fiducial markers are included based on the 4×4 ArUco library[6]. As a risk-reduction system, the spacecraft carries fiducials of two different materials: one uses black silkscreen over white soldermask, while the other comprises regions of gold-plated copper (ENIG process) against a black silkscreen background. The fiducials will be evaluated for long term degradation in the space environment by ground testing of flight spares in a simulated space environment and by potential future imaging of the Tenzing spacecraft by in-space inspection vehicles. The passive RPOD system also includes four RGB indicator LEDs that are visible at ranges up to 100 m and can be used to indicate system status to a chaser vehicle as it approaches to dock. The development of this prototype system and its inclusion in the Tenzing mission will pave the way to widespread commercialization of system elements that can facilitate cooperative and prepared RPOD for passive participants.

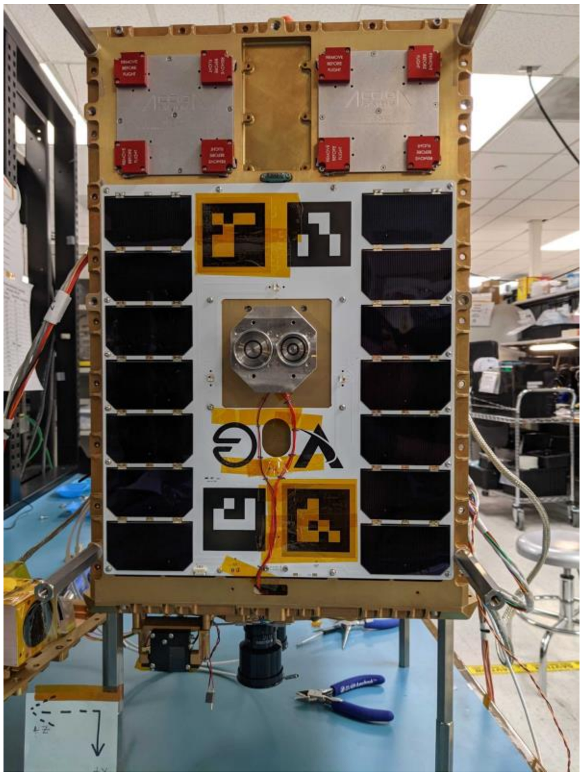

Figure 8: Passive Spark embedded within an Astro Digital smart panel and installed on Tenzing for flight. Kapton tape will be removed before flight

Camera System

High-resolution imaging can provide significant data to support RPOD, including orientation, heading, and diagnostics measurements[7] of remote objects. This data is of significant benefit to in-space propellant tankers and OSAM assets generally. Orbit Fab has partnered with SCOUT Inc. to make the Tenzing mission the first demonstration of the SCOUT-Vision (SpaceCraft Observing and Understanding Things) SmallSat local situational awareness (LSA) payload. The payload consists of stereoscopic fixed-length optics, CMOS sensors, and a dedicated command and data-handling (C&DH) computer for imaging and control loop integration. This prototype was developed by SCOUT Inc. to accommodate timeline and systems constraints for the Tenzing mission. The integrated SCOUT-Vision system is shown in Figure 9. The electro-optical payload affords Tanker-001 sensing redundancy with two cameras, as well as unique experimental operation capabilities: high-precision ranging to 300 m; high-efficacy star tracking; and control loop integration with remote object 6-DoF ephemera extraction via machine learning.

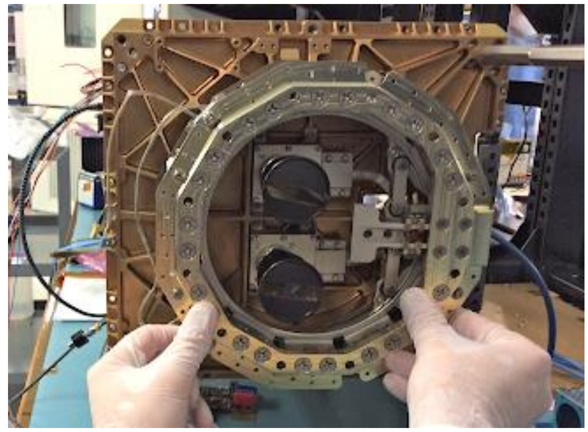

Figure 9: SCOUT-Vision System installed on the Tenzing spacecraft

Sensing Options and Challenges

Introducing a low-power passive sensing system is a cost-effective approach, from engineering and financial perspectives, to de-risk mission operations encompassing RPOD. Ranging has been tackled in myriad missions for decades[7], but the space industry lacks solutions broadly accessible to small satellites for OSAM, formation flight, and local situational awareness applications that might need to operate with cooperative and non-cooperative space objects.

Ground-based space domain awareness (SDA) solutions provide prolific data and a tremendous value proposition for global SDA and conjunction prediction for satellites, but are resolution limited for scenarios such as spacecraft beyond LEO and in clustered formations[8]. Simulated formation flight with a spacecraft in a 150×300-m walking ellipse around a free flyer, using approximations of LEOLabs' tracking capabilities, suffer from relative positioning uncertainty of up to 25% of the ellipse radius.

Conversely, lidar has heritage as an on-board solution for accurate inter-satellite ranging[9], notably in the Northrop Grumman Mission Extension Vehicle (MEV) missions[10], but is hampered by three primary problems for this application:

1. SWaP-C: optical arrays for focusing, transmitting and receiving light; power requirements; heat management
2. Limited operating window: efficacy highly dependent on target surfaces, and ranging only accurate within a narrow distance range
3. Operational flexibility: limited to ranging and single-point spectrometry; transmitted light can interfere with other spacecraft; still

requires secondary and tertiary sensors to contextualize ranging data.

An electro-optical system offers counterpoints to the above, and has historically proven to be predominantly fit for long-range applications, particularly with non-cooperative targets[7]. Electro-optical sensors introduce unique challenges to spacecraft operations, however:

1. Regulatory: space-based imaging requires a license, and few licenses have been issued for non-Earth imaging. Orbit Fab, SCOUT, and Astro Digital successfully collaborated to be issued a commercial license in 2021.
2. Electro-optical systems flown in space have historically suffered from low resolutions and high noise, although this has been mitigated by evolving sensor technology.
3. Images place a tremendous burden on communication systems due to their size.
4. Selecting the "right" images has historically been difficult, necessitating extended downlinks prior to selecting for useful data.
5. Some sensors may be damaged by direct sun exposure during imaging.

Electro-optical System Characteristics

The Tanker-001 SCOUT-Vision payload features a 10°×8° field of view, and was designed for imaging space objects at sub-kilometer ranges up to a maximum range of 2.5 km. Figure 9 simulates the output from imaging a 1.5-m^2 satellite at maximum functional range. Figure 10 shows a simulated image of a similarly sized example satellite taken at a range of 250 m, demonstrating the significant effect of range on imaging resolution for RPOD and inspection systems.

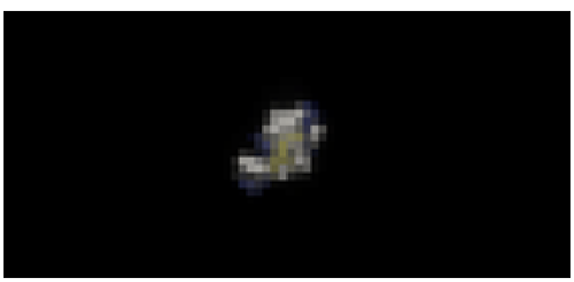

Figure 9: Cropped visualization of 1.5-m^2 spacecraft at a distance of 2.5 km

Figure 10: Cropped visualization of a notional earth imaging spacecraft at a distance of 250 m

The SCOUT-Vision system flown on Tanker-001 has a mass of 800 g and draws 15 W under load. SCOUT's commercial model has a volume of 116×68×200 mm, offering over 3x the resolution and range of the Tenzing prototype.

Image processing and active object detection relies on the implementation of a neural network object detection framework developed by SCOUT. Convolutional neural networks have recently come into growing use for remote object characterization and estimation due to their computational efficiency when properly trained[11], and SCOUT-Vision processes multiple machine learning tasks while operating under different Tanker-001 operating modes.

Initial development of the machine-learning algorithm showcased the value of the evolving methods of feature detection, broader image classification, and object tracking potential of machine learning in the backend of a spacecraft vision payload. Initial builds struggled to achieve <30% false-positive rates at 150 m and further, but the first iteration of SCOUT-Vision software integrated into Tanker-001 achieved ≥99% confidence interval in image classification in its close-operations range after training and testing with sets of 500–4,000 synthetic images. Relative position estimation was also high. A discrete breakdown of efficacy at different ranges follows in Table 1.

Table 1: Overview of object detection confidence intervals in synthetic tests.

Range (m)	Mean Test Set Confidence:

75	>99%
150	>90%
300	>68%
500+	<50%

Automated detection of objects enables a decrease in total downlink requirements. This significantly lowers bandwidth load predictions for heavily image-oriented missions, enabling broader LSA application for small satellites. Further, increased confidence in the detection and relative position of remote objects will enable additional automation of processes such as conjunction avoidance and real-time just-in-time collision avoidance, which may be critical steps to in-space collision and debris mitigation[12].

The implementation of an electro-optical system as a central spacecraft feature can also be employed to perform a dual role as a star tracker, potentially reducing the impact to mission budgets. Star trackers are extremely valuable additions to space missions, offering arcsecond pointing accuracy. Although carefully tuned to provide high-precision measurements in environments where most sensors would fail, they are first and foremost cameras, and can be used for imaging[13]. The reverse is also true; cameras of sufficient image quality can also be used as star trackers. Tanker-001 also features a calibrated star tracker with flight heritage, which will be used as a baseline for experimental testing of stereoscopic star tracking via SCOUT-Vision. SCOUT has been working with partners throughout 2021 to mature the open-source SOST star tracker software[14] and implement it into the mission.

Future SCOUT-Vision payloads and commercial offerings will introduce glint detection and occlusion-based long-range detection capabilities, extending optical detection and ID range to ranges up to 1600 km when supplemented by ground-based services.

The flight and successful demonstration of this imaging payload on the Tenzing mission will help pave the way for commercial satellite inspection and imaging for RPOD.

Proposed Flyby Operation

The system architecture and capabilities of Tanker-001 enable unique mission profiles; Orbit Fab and SCOUT are collaborating on a pathfinder commercial RPO and inspection mission extension following the initial phase of the Tenzing mission. This operation maximizes the potential data generated by Tenzing for future RPOD technology development: the successful execution of a fly-by with imaging verification of another space object means proving RPO maneuvering and imaging capabilities fulfilling commercial customer requirements for various segments of the growing satellite servicing market.

If executed, this fly-by will generate operational knowledge for RPO phases using small spacecraft and provide data to support active RPOD development and commercialization. A controlled fly-by enables the collection of high-quality imagery of the other space object (referred to as the client) and would be a powerful demonstration of the feasibility of completing

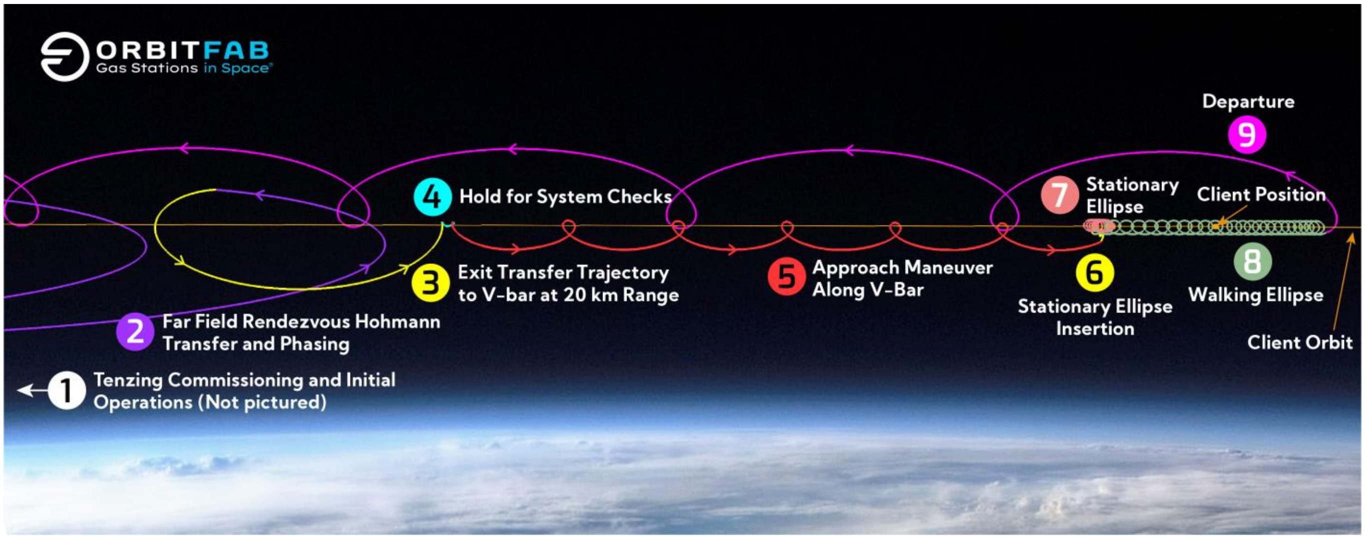

Figure 11: Notional Tenzing flyby trajectory in client-centric coordinate frame.

successful RPO activites in LEO using existing technologies on commercial SmallSats.

To ensure success, the team shall complete a number of activities to verify system functionality prior to the proposed RPO sequence, including:

- Spacecraft bus checkout, including successful commissioning and initial operation completion without anomalies
- Test firing of the Halcyon thruster system and validation of propulsive maneuver simulations
- Measurement of operational orbit determination performance and associated trajectory updates
- Camera system performance verification and experimental image-based capabilities tests

Figure 11 presents the notional trajectory for a fly-by operation using the Tenzing spacecraft, presented in a client-centric coordinate frame. The fly-by notionally begins with a Hohmann transfer maneuver, the segment labeled (2), into an orbit to phase-match Tenzing with the imaging client. Near actual phase alignment, Tenzing will come to a distance of 20 km aligned with the velocity vector (V-bar), at which point it will perform Maneuver (3), cancelling any relative velocity and establishing a hold position. The spacecraft will remain at this point until passing a series of system readiness checks to ensure success of the approach operation (4).

Once all checks are successfully complete, Tenzing will initiate an approach (5) to a range of 3 km from the client over the course of several orbits. Upon arriving at the targeted 3 km range, the spacecraft will enter a stationary ellipse circling the client's V-bar (6). This ellipse will be sized to ensure radial and cross track separation that is large enough for the mission orbit determination algorithms to conclusively verify that there is no risk of collision regardless of in-track separation. Tenzing will remain in this stationary ellipse while undergoing final system readiness checks, then undergo a small maneuver to transition from the stationary ellipse to a walking ellipse (7). The walking ellipse will maintain the same radial and cross track parameters as the stationary ellipse but travel along the V-bar each orbit.

It is crucial to verify that Tenzing's state estimate will predict no possibility of collision with the client following the walking ellipse maneuver. If this cannot be verified, the maneuver will be aborted before Tenzing's in-track position reaches a critical range. If all indications are nominal, Tenzing will continue in this walking ellipse, flying past the client and gathering images from as close of a range as possible as it passes. When it reaches a range of 3 km on the other side of the client, it will execute a departure maneuver along the V-bar (9) which will rapidly bring it away from the client's position.

If successfully completed, this fly-by operation will be a significant milestone in the commercialization of RPOD technologies, and will be the first dedicated commercial RPO and inspection by a SmallSat ever.

Benchmark Propulsion System

Tenzing includes a Halcyon thruster provided by Benchmark Space Systems. The most versatile system in their integrated products line-up combines an HTP thruster developed by legacy Tesseract with Benchmark's fluid handling and flight controller subsystems in a turn-key system offering. The Halcyon takes advantage of readily available catalyst materials in its monopropellant configuration resulting in a reliable non-toxic chemical-class solution with moderate specific impulse and excellent pulse-mode performance for precision operations. For more demanding missions with large movements and demanding mobility requirements, the Halcyon is available in a 'dual mode' configuration, which takes advantage of post-catalyzed gas-gas injection that can double the specific impulse of the unit. This will be the first launch of the Halcyon propulsion system.

LESSONS LEARNED IN THE PATH TO FLIGHT

One of the principal drivers of this mission was to develop the skills and knowledge within Orbit Fab to allow for the mass production of propellant depots to meet economic demands. Orbit Fab and our partners have identified the following lessons learned.

Time spent planning will save time spent making up for a lack of planning.

Even in rapid programs (Tenzing was less than 9 months from start to launch), it is important to take the time whenever possible to properly plan integration flows, processes and tests. Early planning and documentation of these procedures, although often loose and in need of refinement as the mission progresses, is integral to a successful mission. It is essential to revisit and revise these plans as the mission comes to fruition and hardware is built and tested.

Propulsion system testing at the fully integrated propulsion system level is time consuming and difficult

Many propulsion system acceptance and qualification tests require the system to be filled with various test fluids. The process of loading and unloading a fully integrated propulsion system is more time consuming than testing at the component level. Performing as many tests as feasible at the component level can buy down risk and reduce overall schedule time. Orbit Fab took a material test, protoflight and full flight spare approach, but could have completed more component acceptance testing to simplify some system level tests. Orbit Fab completed all fluid system level tests on site at a test house, which necessitated we work within the environment available there. Separating trips for testing and cleaning would have allowed for a simpler post-acceptance test functionality check, but required two sections of travel, made more difficult due to the COVID-19 pandemic. In the future, more in-house testing/cleaning capability could expedite and simplify the production flow.

Disaggregation of wire harness and payloads is essential for clean integration

All independently installable payloads should have distinct wiring interfaces. Tying payloads together makes it difficult to test them independently. The joint reliance on the TCU2 for thermal control of all payloads on Tenzing led to payloads being tied together when the thermal management wire harness was made. This made future individual payload pre-flight ops more difficult to isolate. In addition to isolating payloads, wire harnesses need to be planned in advance with specified routing to ease integration of spacecraft components and prevent harness damage during integration. Further damage can be prevented by ensuring all wire harnesses are inspectable throughout integration with the spacecraft bus. This inspection method needs to be nondestructive and avoid damaging the unit under test, provide temporary access to terminals, and be sealed prior to flight to avoid charging concerns.

Software and hardware need to be developed and tested in parallel rather than in series

The instrumentation and actuators for Tenzing were integrated into the flight unit and engineering model as soon as they contained leads to attach to the final wire harness termination. This was significantly earlier than the embedded software to command these units was ready, and led to unforeseen issues that became apparent later in the program. The pace of the Tenzing mission necessitated early integration, but future missions should have these aspects of the mission developed in parallel to reduce the time from issue development to issue observation.

Testing on the flight hardware will garner faster results

Flatsats only work when they have the required hardware to adequately simulate the flight hardware. Typically, rapid missions like Tenzing end up with incomplete flatsats due to hardware availability and the time-consuming nature of bringing up the system alongside the flight and flight spare units. As a result, complete testing of how the system as a whole behaves when driving different pairings of actuators and instrumentation is often very difficult. Further, flight wiring can present issues that are not present in ground flatsat wiring (i.e; crosstalk on bundles of wire routed near each other on flight systems).

Availability of soft seals in specific sizes and hardness is limited due to long lead times

Due to the long lead times for seals, Orbit Fab was forced to test multiple material options from different vendors in order to ensure there would be working o-rings for each application. This meant that at times, multiple contingency tests had to be performed in parallel and the final configuration features dissimilar seal materials. The pace of the Tenzing mission made it impossible to acquire all the right soft seals or do all the material testing in time for assembly. Spacecraft assembly skills, material selection and best practices can only really be learnt by hands-on development of a spacecraft, and future missions will have this information and know to budget more time.

NEXT STEPS

Tenzing is just the first of many propellant depots to be produced by Orbit Fab and our partners. The next major milestone for development of the technologies needed for the demonstration and commercialization of propellant sales in orbit is a complete end to end demonstration in the LEO or GEO environment. Tenzing positions Orbit Fab and our partners well to tackle this in 2023, following further development and ground demonstration of the RAFTI Space Coupling Half and Smart Prox-ops and Rendezvous Kit (SPARK) RPOD system to ensure their full flight readiness and reliability. The lessons learned in production of Tenzing and to be learnt throughout operation and staging as a propellant depot for future use will benefit orbit fab and our partners for many years and missions to come, the authors hope these lessons may assist other SmallSat builders in the future as well.

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